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CONSIDERATIONS IN BALLISTOCARDIOGRAPHY*

Certain physical and biophysical aspects of ballistocardiography have not been adequately appreciated or understood and as a result rather severe forms of distortion have markedly limited the utility of the procedure. This phase of the subject is extremely complex and technical. However, a general overall picture may be presented in relatively non-technical language with sufficient content so that the average physician may evaluate in a general way what minimal clinical performance may be tolerated and have some understanding as to the limitations and status of the art based upon the physics and biophysics involved.

A ballistocardiogram is a graphic representation with respect to time of the motions which are imparted to the body in response to the physical movements of the heart, the ejection of blood from the heart, and the passage of the blood through the vascular system. The ballistic movements of the body as a result of cardiac action follow in principle Newton's third law of motion which states that "to every action there must be an equal and opposite reaction." The ballistic force vector which imparts the movement to the body is of variable magnitude throughout the cardiac cycle and its spatial direction changes. Furthermore, the magnitude and direction of the instantaneous spatial force vector is not necessarily equal in two normal subjects at the same instant during the cardiac cycle because of dissimilarity in anatomic positioning and the forcefulness of cardiac activity. The amount of movement imparted to the body is in turn dependent upon factors such as compliance of the tissues between the heart and the skeletal structure, the compliance of tissues between the vascular system and the skeletal structure, the compliance of the various skeletal joints, the mode of support of the body, the compliance of the tissue between the skeletal structure and the support, and the elasticity and peripheral resistance of the vascular system.

The ballistocardiograph in its most common form is capable of measuring the ballistic movements of the body axially only—along a line drawn from head to foot. The ballistic forces that exist in the body are spatial, therefore, the common forms of ballistocardiographs merely register the body movements which are produced by the projection of the vector along the head-foot axis; the projected vector is of lesser magnitude than the spatial vector and the body moves a lesser amount axially than in the direction of the spatial vector at that instant of time.

It should be apparent, therefore, that the forces which move the body are not of the same magnitude as at the source and that the degree of modification is unknown and may be variable from subject to subject. *With our present knowledge, this transmission loss must be treated as an unknown quantity and due consideration given it in clinical evaluations.*

When registering and interpreting ballistocardiograms, one should know whether the graph is a representation of the forces generated in the body by cardiovascular activity, or the amount the body is displaced by the cardiovascular forces, or the velocity at which the body is displaced. Practically all of the ballistocardiographic procedures in common use at the present time do not register the ballistic forces, the resultant body displacement, or velocity of movement in its true form, but present a graphic representation of a mixture of these reactions. Some ballistocardiograms are nearer to force representations while others depict body displacement. Let us see why.

If, for example, a Starr bed were used, and if there were rigid coupling present between body and bed so that minute relative movements could not take place, and if the body were rigid, the magnitude of movement imparted to the bed (displacement) would be proportional to the *cardiovascular forces* projected along the head-foot axis. The stiff springed Starr bed, when used in this manner, may be considered in the same sense as a scale which measures rapidly changing forces horizontally. Theoretically, the Starr bed should be an excellent means for measuring ballistocardiographic forces. However, it is impossible to prevent the body from moving

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relative to the bed and the body itself is not rigid. Therefore, the theoretically ideal condition cannot exist in practice and cannot be approximated.

If the same rigid body were suspended in space completely unrestrained, the acceleration of the body during displacement in the head-foot direction would be proportional to the cardiovascular forces projected along the head-foot axis. Thus, the unknown factor due to non-rigid coupling between body and support is eliminated. This condition can be approximated rather closely by procedures which will be discussed.

The relationships between *motion* (which is described in terms of displacement, velocity, or acceleration) and the cardiovascular *forces*, which produce the motion are at present unknown in the Starr, Nickerson and Dock procedures, and their respective supports and restraints are dissimilar. In the case of the Starr bed, the springs are very stiff and the bed is practically undamped. Damping is the process of introducing resistance or friction so that when a force is instantaneously applied, the bed will deflect with a dead beat; it will neither overshoot nor consume excessive time in reaching its destination. The more damping that is introduced, the greater is the restraint to free body movement. The Nickerson bed uses comparatively soft springs with considerable damping. In the Dock system, the body tissues between the skeletal structure and the rigid support act like a spring of moderate stiffness and some damping is introduced by the heel supports.

Therefore, even though the sensing instruments which are used with the Starr, Nickerson or Dock procedures may be true indicators of displacement, velocity or acceleration, the marked effects upon the body motion by the supports and restraints produce marked alterations in the registered ballistocardiograms which are no longer true displacement, velocity, or acceleration representations as indicated by the sensing instruments. Furthermore, when appreciable restraint to body movement is introduced by a rigid or semi-rigid support, the body itself exhibits a rather low oscillatory frequency known as natural frequency. That is, if a force is applied to the body, the skeletal structure will move relative to the support if the support is rigid or semi-rigid. When the force is suddenly released, the skeletal structure will go back to its original relative position with a diminuendo oscillatory motion because the body tissue which is interposed between the support and the skeletal structure acts like a soft spring with little damping. Cardiovascular forces which also produce skeletal movements with respect to the support also set up such trains of diminuendo oscillations in the region of 4-5 complete oscillations per second in the average subject. These oscillations superimpose upon the actual cardio-ballistic body movements and the resultant ballistocardiogram is a summation of the cardiovascular effects and an unrelated entity. In many cases these parasitic body oscillations may be so severe as to mask almost completely the cardiovascular complexes.

In addition, such a system rapidly attenuates the cardio-ballistic vibrations above the natural body frequency of about 4-5 cycles per second. There are vibrations at least as high as 40 cycles per second present in ballistocardiograms which circumvent the limitations inherent in the Starr, Nickerson and Dock techniques. These higher frequency vibrations play an important role in imparting a distinct configuration to the ballistocardiogram as will be apparent later.

Obviously, the theoretically ideal ballistocardiographic procedure of suspending a subject in space cannot be practically achieved and the next best procedure is to utilize a suspension that requires an almost negligible applied force to produce a deflection. This concept was apparently realized by Gordon[1] in 1877 and Henderson[2] in 1905 who suspended beds by means of ropes or wire of considerable length. Such subject loaded ballistocardiographic systems when deflected and released exhibited a very slow pendulum action (technically called a low natural frequency) of less than one cycle or complete oscillation per second. More recently Burger[3] and co-workers constructed a similar ballistocardiograph with a natural frequency of 0.3 cycles per second plus some damping and von Wittern[4] described one with a natural frequency of 0.5 cycles per second and considerably more damping. The system used in my experimental work[5] had a natural frequency of 0.1 to 0.25 cycles per second with either no damping or a very slight amount but much less than that used by Burger and von Wittern.

In my experimental work it was observed that cardiovascular activity and other random movements of the subject tend to set the bed into a rythmic movement which corresponds to its natural frequency. The resultant ballistocardiogram may have this very low rhythmic sway superimposed upon it. This effect is most severe in the displacement ballistocardiogram, less in the velocity, and least in the acceleration or force ballistocardiograms. A very slight amount of damping will eliminate this bed sway effect and not introduce clinically measurable distortion in the ballistocardiogram. That is, the damping must not exceed 20 percent of that needed to produce critical or dead beat damping.

Experimental data and certain forms of computation show that if the natural frequency of the system is above 0.3 cycles per second (Nickerson and von Wittern type beds), and if the damping is as high as that used by Burger, von Wittern and Nickerson, excessive error is introduced which shows up in the following forms:

1. The low and high frequencies do not register with equal sensitivity.

2. Excessive restraint to free body movement is introduced.

3. Temporal distortion is introduced which shifts the position of the ballistic complexes from their true position in the cardiac cycle.

Another very important consideration is the weight of the suspended bed. The Henderson bed weighed nineteen pounds, Burger's eleven and von Wittern's twenty-two. The bed used in my experiments weighed four pounds. Excessive bed weight does the following:

1. Introduces excessive restraint to free body movement.

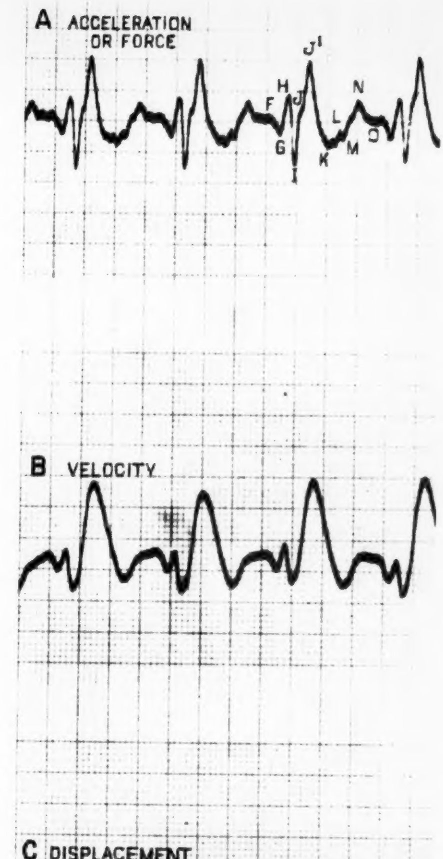
2. Minimizes or eleminates the higher frequency components in the ballistocardiogram.

I have found it inadvisable to use a bed in excess of approximately seven pounds. No apparent differences are noticeable in the ballistocardiograms registered with a four and a seven pound bed.

A so-called aperiodic system such as used by Talbot[6] and co-workers where a lightweight bed is floated in mercury also satisfies the biophysical requirements as does the ultra-low frequency lightweight bed with just enough damping to eliminate sway.

Various forms of sensing devices may be used for registering the bed movements. The one I have found most satisfactory thus far is a modified version of the bar magnet and coil arrangement.[7] The output from this transducer is a measurement of velocity of movement. Operating in conjunction with this sensing device is an electrical arrangement which simultaneously computes at every instant of time the corresponding displacement of the body and the forces which produce the body movements. All three forms of motion may be graphically recorded either simultaneously or separately. This electrical computation procedure is permissible because a distinct mathematical relationship exists between the three forms of ballistocardiographic motion.

In Figure 1 may be seen a simultaneously registered acceleration or force ballistocardiogram, velocity ballistocardiogram, displacement ballistocardiogram and carotid pulse of a typical normal subject. Note in the acceleration or force ballistocardiogram, the complete absence of the 4-5 cycle per second trains of oscillations that are so apparent in ballistocardiograms registered with customary techniques. Also note the sharp deep I wave, the high frequency notchings in the J wave, the absence of the customary appearing K wave, the characteristic appearance of diastole, and especially the pulse like appearance of the displacement ballistocardiogram. *All normal subjects at all ages produce these general ballistocardiographic patterns.*



Characteristic Appearance of the ACCELERATION or FORCE (A), VELOCITY (B), and DISPLACEMENT (C) Ballistocardiograms simultaneously registered with the CAROTID PULSE (D) of a normal subject as obtained with a 0.25 cycle per second undamped bed weighing four pounds.

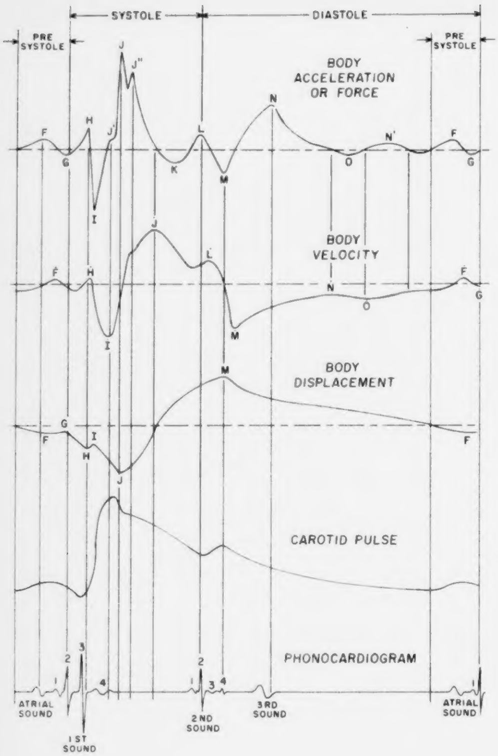


Figure 2 is a composite sketch to illustrate the temporal relationships which are consistently found when the force, velocity and displacement ballistocardiograms are simultaneously registered with the carotid pulse and the phonocardiogram. It is most interesting to note that the force ballistocardiogram complexes consistently assume the following positioning in the cardiac cycle:

F — during atrial systole—occurs simultaneously with the atrial sound.

G — during closure of the A-V valves which corresponds to the second component of the first heart sound.[8]

H — during opening of the semilunar valves —which corresponds to the third component of the second heart sound.[8]

HIJ — the recoil forces of the body due to the forces generated by the primary ventricular ejection—corresponds to the onset of the carotid pulsation.

IJ′ JJ″ — maximum systolic ejection phase. The J′ notch always seems to occur simultaneously with the maximum peak of ventricular-ejection shown in the carotid pulse. The J wave occurs simultaneously with the abrupt change of slope in the carotid pulse just after the maximum ejection phase. The J″ wave occurs at the end of the short plateau in the carotid pulse.

K — reduced ejection.

L — during closure of semilunar valves—corresponds to the second component of the second heart sound.[8]

M — during opening of the A-V valves—corresponds to the fourth component of the second heart sound.[8]

MN — during rapid ventricular inflow phase —occurs simultaneously with the third heart sound.

NON′ — diastasis. A very low amplitude N′ wave is seen in some normals; no relationship to any cardiovascular event has thus far been observed.

The positioning of the ballistic displacement and velocity complexes in the cardiac cycle is apparent from Figures 1 and 2. Some of the more marked differences in the appearance of the force complexes are the abrupt drop off of the H wave and the deep I wave, marked splitting of the J wave in most all normal subjects, absence of or negligible K waves and the high frequencies that are present in the notchings.

CONCLUSIONS

1. The theory and data presented in this discussion indicate that a lightweight undamped or minimally damped bed of ultra-low natural frequency which eliminates several forms of distortion produces force, velocity, and displacement ballistocardiograms of different configuration than is obtainable with the customary Starr, Nickerson and Dock techniques.

2. A primary requirement in ballistocardiography is that the bed shall produce a very minimal impedance to free body movement. A bed which will swing at a rate of 0.3 oscillations per second or slower satisfies this requirement. The bed weight is also an important factor; it must be kept as low as possible. A four pound bed has been found practical and weight of the bed should not exceed about seven pounds. The maximal damping should be just sufficient to eliminate bed sway, this being about 20 percent or less of that necessary for dead beat movement.

3. When minimal impedance to free body movement is present, the body tissues which are interposed between the skeletal structure and the bed cannot act as an undamped soft spring and thereby introduce diminuendo trains of oscillations. These parasitic oscillations produce a

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smoothing-out effect upon the ballistic complexes in systole and mask the diastolic events. Also, the registered temporal relationships between the ballistic complexes and other cardiovascular events become more precise.

4. The losses in the transmission of forces internally in the body are completely unknown. Furthermore, we do not know to what degree these vary from subject to subject. Therefore, the exact determination of cardiac output from the ballistocardiogram is unwarranted; gross relative changes in cardiac output in an individual may have clinical application.

5. When various cardiovascular events are simultaneously registered with ballistocardiograms using the suggested ultra-low frequency technique, the presence of clinically negligible temporal distortion is indicated. This is not true with the Starr, Nickerson and Dock techniques. Thus the duration, configuration, and position of the various ballistic complexes in the cardiac cycle may have more clinical significance than exact magnitude evaluation.

6. Changes in ballistocardiographic configuration in the abnormal subject may be due to marked changes in the velocity of the blood flow. Marked variations in blood velocity will markedly alter the configuration of the force ballistocardiogram. If such is the case, the force and velocity ballistocardiograms should give the most significant information in abnormal conditions.

7. Extensive studies should be undertaken in normal and pathological conditions with the ultra-low frequency technique outlined or with equivalent aperiodic systems and the data compared with what has been accumulated with presently used techniques. Such data may help to eliminate the many disagreements which exist between users of the various techniques who are now making evaluations on an empirical basis with techniques of unknown and variable characteristics.

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The opinions and conclusions expressed herein are those of the author and do not necessarily represent the official views of the Scientific Council of the American Heart Association.

PAPERS FOR THE SCIENTIFIC SESSIONS

All those wishing to present papers at the 28th Scientific Sessions of the American Heart Association must submit abstracts for review by the Program Committee. Abstracts shall not be more than *300 words* and must be submitted in duplicate before *July 1, 1955*, to the Medical Director, American Heart Association, 44 East 23rd Street, New York 10, New York. Abstracts should contain in summary form the results obtained and conclusions reached — *not* a statement that these will be presented at the meeting.

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Sunday, October 23rd	28th Annual Scientific Sessions First Annual Program of Council on Community Service and Education
Monday, October 24th	28th Annual Scientific Sessions Joint Program—Council on Community Service & Education and Council on Rheumatic Fever and Congenital Heart Disease
Tuesday, October 25th	A.H.A. Assembly Panel Meetings
Wednesday, October 26th	Annual Meeting of A.H.A. Assembly—elections—panel reports Annual Meeting Staff Conference of Heart Associations

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